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# ON THE POSSIBILITY OF MONITORING SMALL DEFORMATIONS OF AUSTENITIC MEDIUM-MANGANESE STEELS USING THE MAGNETOMETRIC METHOD

***Purpose***. *Development of a methodology for monitoring small deformations of austenitic medium-manganese steels using magnetometric methods. Determination of the paramagnetic parameter of austenitic steel, the value of which uniquely correlates with the degree of plastic deformation by compression.*

***Research methods***. *Determination of the specific magnetic susceptibility of the sample, the resulting specific magnetic susceptibility of the paramagnetic austenite of the sample, and the paraprocess of α-phase of the sample were performed on an automated Faraday magnetometric balance. Uniaxial plastic compression deformation at room temperature was performed on a laboratory setup.*

***Results***. *Based on the results of experimental studies, the amounts of α'-martensite arising during plastic deformation by compression of 110G8L steel were determined. The resulting (paramagnetic austenite of the sample and the paraprocess of α-phase of the sample) specific magnetic susceptibility of deformed samples of 110G8L steel was experimentally found.*

***Scientific novelty***. *The idea of the relationship between the degree of deformation of austenitic steel and the value of the resulting specific magnetic susceptibility* $\chi_{\propto}$ *(paramagnetic austenite of the sample and the paraprocess of α-phase of the sample) is proposed and experimentally confirmed.*

***Practical value***. *During operation, parts made of austenitic medium-manganese steels are subjected to static or dynamic loads under abrasive wear conditions. This operating mode is accompanied by plastic deformation due to compression. The degree of deformation is an important parameter for assessing the reliability of the product. Determining the degree of deformation by measuring geometric dimensions is not always appropriate, as the configuration of cast parts can be quite complex. At the same time, magnetometric deformation monitoring, specifically the correlation found between the degree of plastic deformation due to compression and the resulting specific magnetic susceptibility, allows to determine the degree of deformation of a part of any configuration.*

***Key words***: *austenitic steel, magnetic susceptibility, deformation, strain-induced martensite.*

## Introduction

Austenitic manganese steels possess a range of valuable properties, leading to their use as structural materials in the mining industry for crushing and grinding equipment [1-3]. Good ductility, strain-hardening ability, and high wear resistance are essential requirements for components operating under intense dynamic loads [4]. However, in practice, depending on the intended use of the components, the optimal chemical composition of the steel is determined, primarily the manganese and carbon content [5, 6]. For low-medium impact loads, metastable 110G8L steel is used [7].


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This steel is metastable and undergoes a martensitic transformation $\gamma \rightarrow \alpha'$ (strain-induced α′-martensite) during plastic deformation. The martensitic transformation is significantly affected by the steel chemical composition, microstructure, deformation temperature, mechanical stress, particle irradiation, etc. This strain-induced transformation is one of the main factors affecting the wear resistance of steel during service [3, 4, 8]. Martensitic transformation provides additional hardening and thus increases the strength and uniform elongation of materials. Thus, the degree of austenite stability is a key factor in martensitic transformation and is related to its morphology, size, carbon and manganese content [9].

### Analysis of research and publications

In [10], a magnetometric method was proposed to assess the structural changes occurring during deformation of austenitic steel. That is, changes in the atomic-crystalline structure of steel during operation are reflected in its magnetic state, which will be determined by the ratio of paramagnetic austenite (γ) and ferromagnetic α′-martensite.

Moreover, if the regularities of $\gamma \rightarrow \alpha'$ transformations at comparatively large plastic deformations have been studied quite well [11, 12], however experimental data at small plastic deformations are practically absent. This is due to the fact that when determining low contents of the α-phase, which arises during deformation, the magnetization of the paramagnetic austenitic matrix is not taken into account, which leads to large errors. For example, the relative error is over 1000% with an α-phase content within 0.005 %, 80 % at 0.1%, and only with an α-phase content of approximately 2.5...3.0% does the error reach ~3%.

Therefore, to study relatively small deformations of austenitic medium-manganese steels, at which a very low content of deformation-induced martensite arises, the integral physical method of α-phase identification [13] was used, which takes into account the magnetization of the paramagnetic austenitic matrix.

### The purpose of the work

The aim of the study is to develop a method for monitoring small deformations of austenitic medium-manganese steels using the magnetometric method and to determine a parameter that can be used for estimation of the degree of plastic deformation by compression.

### Research material and methodology

The object of the study was cast manganese steel 110G8L with the following chemical composition (wt.%): 1.14 C, 8.60 Mn, 0.66 Si, 0.04 S, 0.088 P, 0.10 Cr, 0.019 Al. Steel ingots of 100×100×200 $mm^3$ were obtained in induction crucible electric furnaces by the smelting method in the foundry laboratory of National University Zaporizhzhia Polytechnic. The steel was preliminarily annealed at a temperature of 1323 *K* (30 min.) and quenched in water. Then, samples with dimensions of ~3×3×1 $mm^3$ were cut out using a cold mechanical method. To remove surface damage, the samples were ground on abrasive powders and then polished to a mirror shine with diamond pastes and an electrochemical method. The degree of plastic uniaxial compression strain *D* at room temperature was calculated from the ratio of the thicknesses before ($d_0$) and after (*d*) deformation $D=(d-d_0)/d_0$. At all stages of sample preparation, special attention was paid to ensuring that the sample surface was not contaminated with any ferromagnetic impurities.

The very low content of ferromagnetic carbides and deformation α′-martensite in volume percent was determined by a sensitive magnetometric method, taking into account the magnetization of the paramagnetic austenite matrix [10]. The amount *P* of ferrophase was determined by the formula [10]:

$$P = \frac{\sigma_m}{\sigma_\alpha} \cdot 100\% = \frac{\left[\chi - (\chi_0 + \chi_p)\right] \cdot H}{\sigma_\alpha} \cdot 100\%, \quad (1)$$

where $\sigma_m$ is the ferromagnetic component of the specific saturation magnetization of the sample; $\sigma_\alpha$ is the specific saturation magnetization of the α- phase; χ is the specific magnetic susceptibility of the sample; $\chi_\infty$ is the resulting specific magnetic susceptibility $\chi_0$ of the paramagnetic austenite of the sample and the paraprocess $\chi_p$ of the α-phase of the sample: $\chi_\infty = \chi_0 + \chi_p$; *H* is the magnetic field strength.

From the experimental dependence curves $\chi = f(1/H)$, the values $\chi_\infty$ were found by extrapolation and the amount of ferromagnetic phase was determined in volume percent.

### Research results

In the cast state, the structure of the steel that was investigated was an austenitic base with inclusions of large carbides. After quenching, 110G8L steel samples exhibited an austenitic structure with a small amount of residual carbides. Measurements of magnetic parameters and the amount of ferrophase were performed on the sample after each act of compression. Figure 1 shows typical experimental dependences of the specific magnetic susceptibility $\chi$ on the reciprocal magnetic field (1/*H*) of 110G8L steel at various degrees of relative compression strain *D*.

As can be seen from Figure 1, extending the straight lines with the ordinate axis ($H \rightarrow \infty$) yields $\chi_\infty$ values, and the resulting ferrophase content $P_\alpha$ in volume percent after each specimen deformation is calculated using the formula (1) (are listed in the Table 1). The presence of ferromagnetic carbides in the initial state at zero strain ($D$ = 0) of 110G8L steel is confirmed by the slope of the experimental dependence of the specific magnetic susceptibility χ on the reciprocal of the magnetic field 1/*H* (Fig. 1a, line 1).


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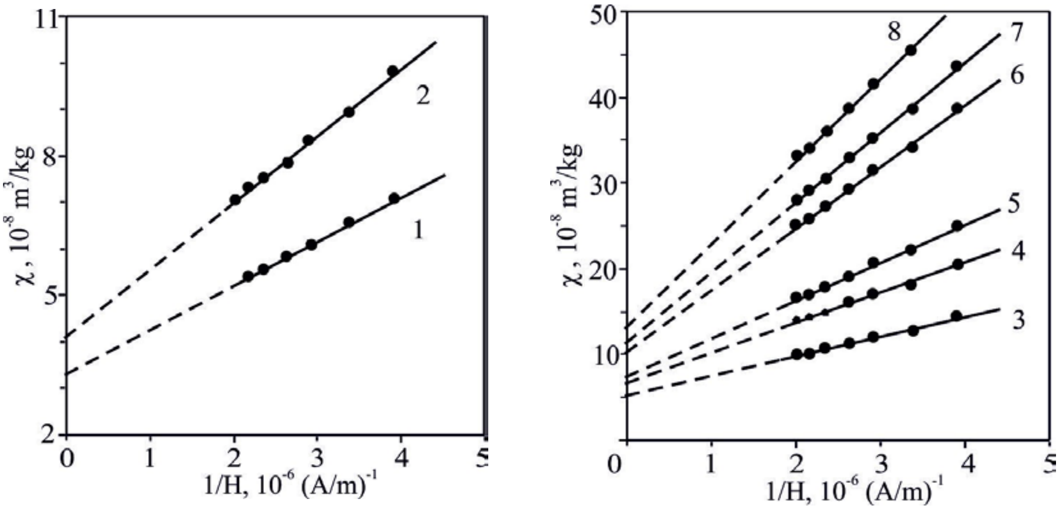


*a* *b*

**Figure 1.** Dependence of the specific magnetic susceptibility χ of a 110G8L steel sample on the reciprocal value of the magnetic field strength *H* at different values of deformation *D*:
*a* – 1 – 0, 2 – 2.48 %; *b* – 3 – 5.82 %, 4 – 8.80 %, 5 – 10.57, 6 – 14.01 %, 7 – 16.49 %, 8 – 17.91 %

The determined amount of ferromagnetic carbides $P_c$ = 0.071% are listed in the Table 1.

For different degrees of relative strain *D*, the total amount of ferromagnetic phases $P_\alpha$ was calculated. It was taken into account that $P_\alpha = P_c + P_{\alpha'}$, where $P_c$ and $P_{\alpha'}$ are the amounts of ferromagnetic carbides and deformation-induced α′- martensite in volume percent (Table 1).

It is assumed that at a carbon content of less than 2 wt.% and moderate deformations, carbides do not form. If we assume that this amount of ferromagnetic carbides (0.071%) does not participate in the formation of deformation-induced α′-martensite and subtract it from the resulting amount of ferrophase $P_\alpha$, we obtain the amount $P_{\alpha'}$ of deformation-induced α′- martensite.

**Table 1 –** Values of the total specific magnetic susceptibility of the sample χ (at $H = 2.55\ 10^5$ A/m), the resulting (paramagnetic austenite and paraprocess) specific magnetic susceptibility $\chi_\infty$ and the amount $P_{\alpha'}$ of α′-martensite deformation depending on the degree of deformation of the 110G8L steel sample

| *D*, % | χ, $10^{-8}$ $m^3/kg$ | $\chi_\infty$, $10^{-8}$ $m^3/kg$ | $P_\alpha$, % | $P_{\alpha'}$, % |
|---|---|---|---|---|
| 0 | 7.03 | 3.29 | 0.071 | 0 |
| 2.48 | 9.75 | 4.10 | 0.107 | 0.036 |
| 5.82 | 1.41 | 5.23 | 0.168 | 0.098 |
| 8.80 | 2.04 | 6.58 | 0.261 | 0.190 |
| 10.57 | 2.46 | 7.39 | 0.326 | 0.255 |
| 14.01 | 3.84 | 1.03 | 0.532 | 0.461 |
| 16.49 | 4.33 | 1.13 | 0.604 | 0.533 |
| 17.91 | 5.05 | 1.40 | 0.689 | 0.619 |

Figure 2 shows the dependence of the formed amount $P_{\alpha'}$ of α′-martensite on the degree of compression deformation *D*. The relationship between these quantities is well described by a second-degree polynomial $P_{\alpha'} = 13.51 \cdot D^2 + 1.1621 \cdot D - 0.0044$ with a confidence level of $R^2$ = 99.38. Note that for 110G8L steel, deformation-induced α′-martensite is formed immediately after the first small compression events.

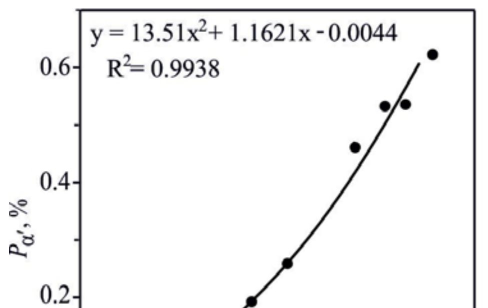


**Figure 2.** Dependence of the amount of $P_{\alpha'}$ of α′- martensite in 110G8L steel vs the degree *D* of compression deformation

The operation of 110G8L steel parts under dynamic loading is accompanied by plastic deformation. Determining the degree of deformation by measuring geometric dimensions is not always appropriate, as the configuration of cast parts can be quite complex. To create a deformation map of a part during operation, it is necessary to cut samples with dimensions of 1–5 mm from its structure at different points. The magnetic susceptibility of the sample is


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then measured using a Faraday balance (or another magnetometric method) to obtain a dependence similar to Fig. 1. The resulting specific magnetic susceptibility $\chi_\infty$ is determined by extrapolation.

Using the correlation between the degree *D* of plastic deformation and the resulting specific magnetic susceptibility $\chi_\infty$ shown in Fig. 3, the degree of deformation of the 110G8L steel sample can be monitored.

Using the equation (the trend line) $D = 0.1288 \cdot ln(\chi_\infty) + 2.2172$ will allow us to determine the degree of plastic deformation by compression with a confidence level of $R^2 = 99.65\%$. For example, if the value of the resulting specific magnetic susceptibility $\chi_\infty = 6 \cdot 10^{-8}$ $m^3$/kg, then the degree of plastic deformation by compression of this sample (part fragment) *D* = 0.075% (Fig. 3).

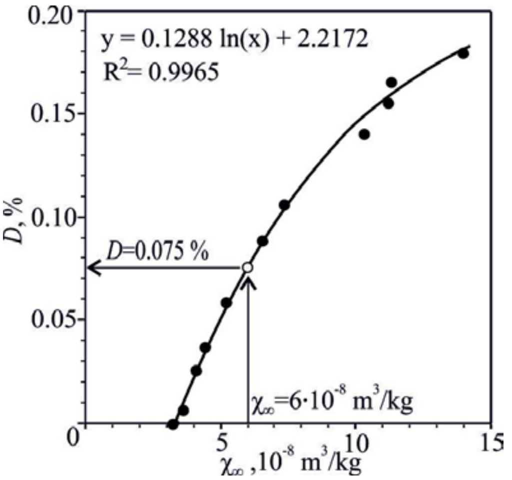


**Figure 3.** Determination (control) of small deformations (relative degree of compression) of 110G8L steel by the value of the resulting (paramagnetic austenite and paraprocess) specific magnetic susceptibility $\chi_\infty$

## Discussion

Using $\chi_\infty$ as an evaluation criterion is more appropriate than using the specific magnetic susceptibility $\chi$ of the sample. This is because using the specific magnetic susceptibility of the sample $\chi$ requires an exact match to the magnetic field strength *H*, which may be technically incompatible for different magnetic setups (due to the different magnetic field strength ranges).

The resulting specific magnetic susceptibility $\chi_\infty$ can be determined from two $\chi$ values at different magnetic fields. Therefore, using the parameter $\chi_\infty$ is more appropriate.

## Conclusions

1. To determine the actual, very low volume percent content of strain-induced $\alpha'$-martensite, a method was used that takes into account the magnetic moment of paramagnetic austenite. Uniaxial compression of 110G8L steel produces strain-induced $\alpha'$-martensite, the amount of which, depending on the degree of deformation, can be mathematically described by a second-degree polynomial.

2. A correlation was found between the magnitude of small deformations (relative compression ratio) of 110G8L steel and the resulting (paramagnetic austenite and paraprocess) specific magnetic susceptibility $\chi_\infty$. This correlation enables strain monitoring using magnetometric methods.

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# ПРО МОЖЛИВІСТЬ КОНТРОЛЮ МАЛИХ ДЕФОРМАЦІЙ АУСТЕНІТНИХ СЕРЕДНЬОМАРГАНЦЕВИХ СТАЛЕЙ МАГНЕТОМЕТРИЧНИМ МЕТОДОМ

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***Мета роботи.*** *Розробка методики контролю малих деформацій аустенітних середньомарганцевих сталей магнетометричним методом. Визначення парамагнітного параметра аустенітної сталі, величина якого однозначно корелює зі ступенем пластичної деформації стисненням.*

***Методи дослідження.*** *Визначення питомої магнетної сприйнятливості зразка, результуюча питома магнетна сприйнятливість парамагнітного аустеніту зразка та парапроцесу* α *-фази зразка здійснювалося на автоматизованих магнетометричних вагах Фарадея. Пластична одновісна деформація стиском при кімнатній температурі виконувалася на лабораторній установці.*

***Отримані результати.*** *Виходячи з результатів експериментальних досліджень, визначено кількість* α'*-мартенситу, що виникає при пластичній деформації стисненням сталі 110Г8Л. Експериментально знайдено результуючу (парамагнетного аустеніту зразка та парапроцесу* α' *-фази зразка) питому магнетна сприйнятливість деформованих зразків сталі 110Г8Л.*

***Наукова новизна.*** *Запропоновано та експериментально підтверджено ідею про зв'язок між ступенем деформації аустенітної сталі та величиною результуючої питомої магнетної сприйнятливості* $\chi_\infty$ *(парамагнетного аустеніту зразка та парапроцесу α-фази зразка).*

***Практична цінність.*** *Деталі з аустенітних середньомарганцевих сталях у процесі експлуатації зазнають статичного чи динамічного навантаження в умовах абразивного зносу. Такий режим роботи деталей супрово-*


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*джується пластичною деформацією стисненням. Ступінь деформації є важливим параметром оцінки надійності виробі. Визначення ступеня деформації виміром геометричних розмірів не завжди прийнятний, так як конфігурація литих деталей може бути досить складною. В той час, магнетометричний метод контролю деформації, а саме знайдена кореляція між ступенем пластичної деформації стисненням і величиною результуючої питомої магнетної сприйнятливості дозволить визначити ступінь деформацій деталі будь-якої конфігурації.*

***Ключові слова:*** *аустенітна сталь, магнетна сприйнятливість, деформація, мартенсит деформації.*

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